DØnote 4370

# Flavor oscillations in $B_d^0$ mesons with opposite-side muon tagging


The DØ Collaboration

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$B_d^0 - \bar{B}_d^0$ oscillations were studied with a large semileptonic sample corresponding to approximately 250 pb$^{-1}$ of integrated luminosity accumulated with the DØ Detector in Run II. The flavor of the final state of $B_d^0$ meson was determined using the muon charge from the partially reconstructed decay $B_d^0 \to \mu^+ D^*(2010)^- X$, $D^*(2010)^- \to \bar{D}^0 \pi^-$, $\bar{D}^0 \to K^+ \pi^-$. The opposite-side muon tagging method was used for the initial-state flavor determination. The $B_d^0$ meson oscillation frequency was measured to be equal to:

$$\Delta m = 0.506 \pm 0.055 \text{ (stat) } \pm 0.049 \text{ (syst) ps}^{-1}$$

This result is in agreement with the world average and this measurement is an important step toward $B_s$ oscillation measurement.


*Preliminary Results for Winter 2004 Conferences*

## I. INTRODUCTION

The measurement of flavor oscillations in $B_d^0$ mesons is an important topic in modern heavy flavor physics. The oscillations are explained in the Standard Model by box diagrams with top quarks and W bosons in the loop (Fig. 1). Those diagrams give rise to the difference between the two $B_d^0$ meson mass eigenstates, $\Delta m$. The precise measurement of the oscillation parameter $\Delta m$ allows determination of the product of the CKM matrix elements $|V_{tb}V_{td}^*|^2$, see [1] for a recent overview of the subject.

The value of $\Delta m$ has been measured with high precision at B-factories. The world average given in [2] is

$$\Delta m = 0.502 \pm 0.007 \text{ ps}^{-1} \tag{1}$$

The study of the $B_d^0 - \bar{B}_d^0$ mixing at the Tevatron is a benchmark measurement useful for understanding of the initial-state flavor tagging. Observation of oscillations in the $B_s$ system is a major goal of the Tevatron physics program and there will be a lot of similarities between the flavor tagging for the $B_s$ and $B_d^0$ mesons. It is also interesting because some theories predict "new physics" specific for hadron colliders (see for example [3]) which can affect the outcome of the mixing measurement for $B_d^0$ mesons at the Tevatron.

The analysis reported here exploits a large semileptonic sample corresponding to approximately 250 pb$^{-1}$ of integrated luminosity, accumulated by DØ during the period from April 2002 to January 2004. $B$ hadrons were selected using their semileptonic decays $B \to \mu^+ D^{*-} X$ (charge conjugated states are always implied in this paper) with reconstructed $D^{*-} \to \bar{D}^0 \pi^-$ decays. Both simulation and available experimental results show that this sample is dominated by $B_d^0 \to \mu^+ \nu D^{*-} X$ decays and can therefore be used to study oscillations of neutral B mesons.

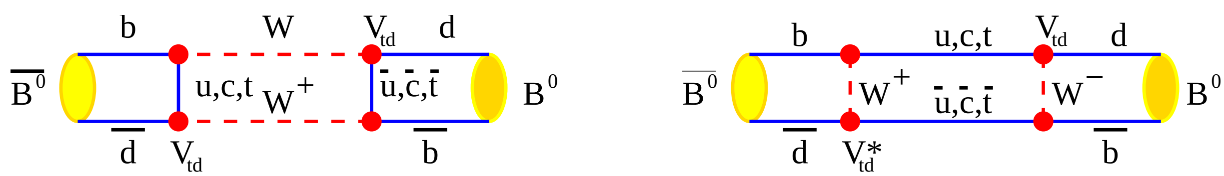


FIG. 1: Box diagrams responsible for $B_d^0 - \bar{B}_d^0$ oscillations.

## II. DETECTOR DESCRIPTION

The following main elements of the DØ detector are essential for this analysis:

- A magnetic central-tracking system, which consists of a silicon microstrip tracker (SMT) and a central fiber tracker (CFT), both located within a 2 T superconducting solenoidal magnet;
- A muon system located beyond the calorimetry.

The SMT has $\approx 800,000$ individual strips, with typical pitch of $50 - 80$ $\mu$m, and a design optimized for tracking and vertexing capability at $|\eta| < 3$. The system has a six-barrel longitudinal structure, each with a set of four layers arranged axially around the beam pipe, and 16 radial disks. The CFT has eight thin coaxial barrels, each supporting two doublets of overlapping scintillating fibers of 0.835 mm diameter, one doublet being parallel to the collision axis, and the other alternating by $\pm 3°$ relative to the axis. Light signals are transferred via clear light fibers to solid-state photon counters (VLPC) that have $\approx 80\%$ quantum efficiency.

The muon system consists of a layer of tracking detectors and scintillation trigger counters before 1.8 T toroids, followed by two additional layers after the toroids. Tracking at $|\eta| < 1$ relies on 10 cm wide drift tubes, while 1 cm mini-drift tubes are used at $1 < |\eta| < 2$.

## III. DATA SAMPLE

This analysis uses the $B \to \mu^+ D^*(2010)^- X$ data sample selected with the offline filter from all data available before 1/21/2004 with no trigger requirement.

The selections for the offline filter are described below.

### A. Event selection

For this analysis, muons were required to have transverse momentum $p_T^\mu > 2$ GeV/c as measured in the central tracker, pseudo-rapidity $|\eta^\mu| < 2$ and total momentum $p^\mu > 3$ GeV/c.

All charged particles in a given event were clustered into jets using the DURHAM clustering algorithm [4]. Events with more than one identified muon in the same jet were rejected, as well as events with identified $J/\psi \to \mu^+\mu^-$ decays.

The $\bar{\mathrm{D}}^0$ candidate was constructed from two particles of the opposite charge belonging to the same jet as the reconstructed muon. Both particles are required to have transverse momentum $p_T > 0.7$ GeV/c, and pseudo-rapidity $|\eta| < 2$. They were required to form a common $D$-vertex with good fit $\chi^2$. For each particle, the axial (plane perpendicular to the beam direction) $\epsilon_T$ and stereo (plane parallel to the beam direction) $\epsilon_L$ projections of the track impact parameter with respect to the primary vertex together with the corresponding errors ($\sigma(\epsilon_T)$, $\sigma(\epsilon_L)$) were computed. The combined significance $\sqrt{(\epsilon_T/\sigma(\epsilon_T))^2 + (\epsilon_L/\sigma(\epsilon_L))^2}$ was required to be greater than 2. The distance $d_T^D$ between the primary and $D$ vertices in the axial plane was required to exceed 4 standard deviations: $d_T^D/\sigma(d_T^D) > 4$. The accuracy of the distance $d_T^D$ determination was required to be better than 500 $\mu$m. The angle $\alpha_T^D$ between the $\bar{\mathrm{D}}^0$ momentum and the direction from the primary to the $\bar{\mathrm{D}}^0$ vertex in the axial plane was required to satisfy the condition: $\cos(\alpha_T^D) > 0.9$.

The tracks of muon and $\bar{\mathrm{D}}^0$ candidate were required to form a common $B$-vertex with good fit $\chi^2$. The momentum of the $B$-candidate was computed as the sum of the momenta of the $\mu$ and $\bar{\mathrm{D}}^0$. The mass of the $(\mu^+\bar{\mathrm{D}}^0)$ system was required to fall within $2.3 < M(\mu^+\bar{\mathrm{D}}^0) < 5.2$ GeV/c$^2$. If the distance $d_T^B$ between the primary and $B$ vertices in the axial plane exceeded $4\sigma(d_T^B)$, the angle $\alpha_T^B$ between the $B$ momentum and the direction from the primary to the $B$-vertex in the axial plane was demanded to satisfy the condition $\cos(\alpha_T^B) > 0.95$. The distance $d_T^B$ was allowed to be greater than $d_T^D$, provided that the distance between the B and D vertices $d_T^{BD}$ was less than $3\sigma(d_T^{BD})$. The error $\sigma(d_T^B)$ was required to be less than 500 $\mu$m.

The masses of kaon and pion were assigned to the particles according to the charge of the muon, requiring the $\mu^+K^+\pi^-$ final system or its charge conjugate.

For the $\mu^+\bar{\mathrm{D}}^0$ candidates, we search for an additional pion with $p_T > 0.18$ GeV/c and the charge opposite to the charge of the muon. The mass difference $\Delta M = M(\bar{\mathrm{D}}^0\pi) - M(\bar{\mathrm{D}}^0)$ for all such pions when $1.75 < M(\bar{\mathrm{D}}^0) < 1.95$ GeV/c$^2$ is shown in Fig. 2. The peak, corresponding to the production of $\mu^+\mathrm{D}^{*-}$ is clearly seen. The total number of $\mathrm{D}^{*-}$ candidates in the peak is equal to 25680 $\pm$ 230. In the fit function the signal and background have been approximated by a sum of two Gaussians and by a sum of an exponential and a linear function, respectively.

## IV. INITIAL-STATE TAGGING WITH OPPOSITE-SIDE MUONS

Opposite-side muon tagging of the initial flavor of the B meson exploits the fact that in the $b\bar{b}$ pair production there are always two particles in the final state containing b-quarks. Typically those are two-jet events with two B mesons in two back-to-back jets, but the final state could also contain a B baryon and/or have more than two jets. In addition if the two b-jets originated from the flavor excitation or gluon splitting processes the angle between the jets is not necessarily close to 180 degrees but varies within a rather wide range.

The second B meson (or baryon) is used to tag the original flavor of the reconstructed $\mathrm{B}_d^0$ meson. In the case of semileptonic decays the lepton charge of the B used for tagging will be opposite to the lepton charge of the reconstructed B for non-oscillated reconstructed B mesons, whereas the lepton charge will be the same for oscillated B mesons.

Muons with $p_T > 2.5$ GeV/c and $\cos(\phi$ *angle between* $\mu^+\bar{\mathrm{D}}^0$ *and tag muon*$) < 0.5$ were considered for tagging. If more than one tag muon candidate per event is found the candidate with higher $p_T$ is chosen. The number of $\mathrm{D}^{*-}$ before and after tagging was found to be equal respectively to $25680 \pm 230$ and $1222 \pm 36$. The fraction of tagging estimated as the ratio of these two numbers is therefore equal to $(4.76 \pm 0.19)\%$.

## V. EXPERIMENTAL OBSERVABLES $A_i$

The transverse decay length of a $B$-hadron $L_{xy}$ was defined as the distance in the axial plane between the primary vertex and vertex produced by the muon and $\bar{\mathrm{D}}^0$. The vertexing algorithm is described in detail in [5]. The transverse momentum of a $B$-hadron $P_T^{\mu \mathrm{D}^0}$ was defined as the vector sum of transverse momenta of muon and $\bar{\mathrm{D}}^0$. The sign of the decay length was set positive, if the angle $\alpha_T^B$, defined in section III, was less than $\pi/2$, otherwise it was set negative. The measured *visible proper decay length* (VPDL) was defined as $x^M = L_{xy} \cdot M_B \cdot c/P_T^{\mu \mathrm{D}^0}$.

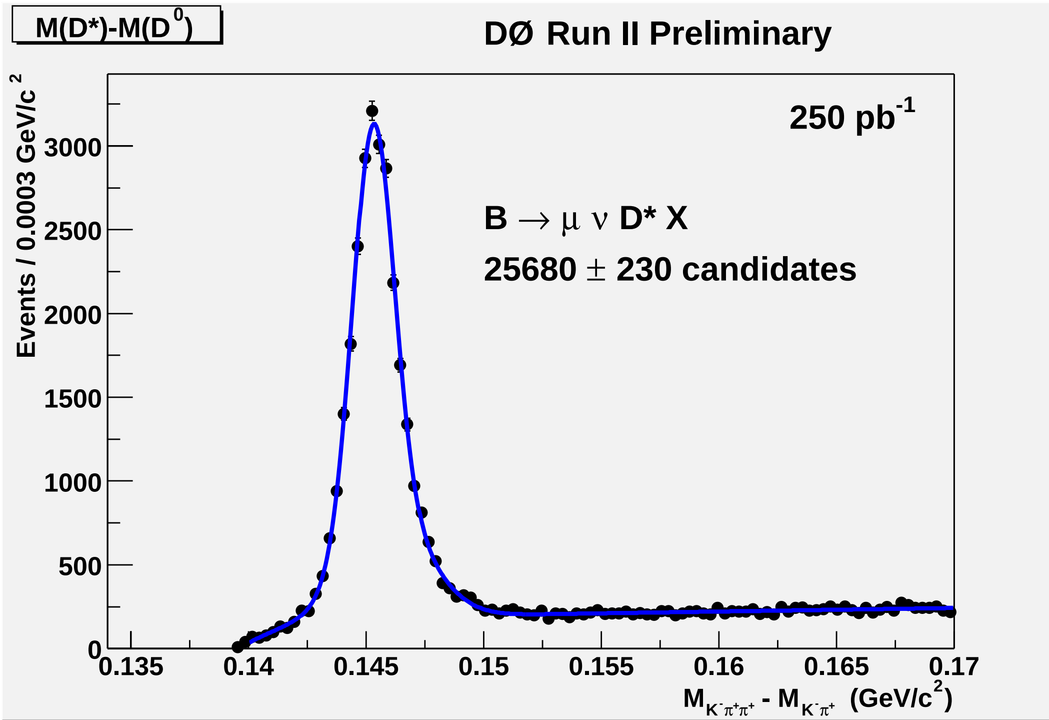


FIG. 2: The mass difference $M(\mathrm{D}^0\pi) - M(\mathrm{D}^0)$ for events with $1.75 < M(\mathrm{D}^0) < 1.95$ GeV/c$^2$. The total number of $\mathrm{D}^{*-}$ candidates in the peak is equal to 25680 $\pm$ 230. In the fit function the signal and the background have been approximated by a sum of two Gaussians and by a sum of an exponential and a linear function, respectively.

TABLE I: Definition of 7 intervals in VPDL. For each interval the measured number of $\mathrm{D}^{*-}$ for the opposite sign and same sign of muon tag $N_i^{non-osc}$, $N_i^{osc}$, their statistical errors $\sigma(N_i^{non-osc})$, $\sigma(N_i^{osc})$, all determined from the fits of corresponding mass difference $M(\mathrm{D}^0\pi) - M(\mathrm{D}^0)$ distributions, the measured asymmetry $A_i$, its error $\sigma(A_i)$ and the expected asymmetry $A_i^e$ corresponding to $\Delta m = 0.506$ ps$^{-1}$ are given.

| group | VPDL range, cm | $N_i^{non-osc} \pm \sigma(N_i^{non-osc})$ | $N_i^{osc} \pm \sigma(N_i^{osc})$ | $A_i \pm \sigma(A_i)$ | $A_i^e$ |
|---|---|---|---|---|---|
| 1 | [-0.025, 0] | $38.9 \pm 6.4$ | $20.8 \pm 4.7$ | $0.304 \pm 0.128$ | 0.451 |
| 2 | [0, 0.025] | $156.3 \pm 13.8$ | $60.6 \pm 8.8$ | $0.441 \pm 0.068$ | 0.442 |
| 3 | [0.025, 0.05] | $185.8 \pm 14.0$ | $79.5 \pm 9.3$ | $0.401 \pm 0.058$ | 0.397 |
| 4 | [0.05, 0.075] | $129.4 \pm 9.9$ | $59.7 \pm 8.0$ | $0.369 \pm 0.067$ | 0.313 |
| 5 | [0.075, 0.1] | $73.3 \pm 8.9$ | $49.7 \pm 7.3$ | $0.192 \pm 0.092$ | 0.202 |
| 6 | [0.1, 0.125] | $41.7 \pm 7.2$ | $38.7 \pm 6.7$ | $0.037 \pm 0.122$ | 0.082 |
| 7 | [0.125, 0.25] | $62.1 \pm 8.8$ | $80.6 \pm 9.4$ | $-0.130 \pm 0.090$ | -0.112 |

Events were divided into 7 groups according to the measured VPDL. The number of $\mu^+\mathrm{D}^*$ events with positive ("oscillated") and negative ("non-oscillated") tags, $N_i^{osc}$ and $N_i^{non-osc}$, in each interval $i$ of VPDL were determined from a fit of the $\mathrm{D}^*$ peak in the mass difference $M(\mathrm{D}^0\pi) - M(\mathrm{D}^0)$ distribution.

The experimental observables, asymmetry $A_i$ in each VPDL bin, for this measurement were defined as:

$$A_i = \frac{N_i^{non-osc} - N_i^{osc}}{N_i^{non-osc} + N_i^{osc}}. \tag{2}$$

Intervals of VPDL, the number of "non-oscillated" and "oscillated" events, the asymmetries and the corresponding errors derived from the fit in each VPDL bin are given in Table I. Fig. 3 shows the asymmetry as a function of the visible proper decay length.

## VI. FITTING PROCEDURE AND RESULTS

The D$^*$ sample is composed mostly of B$_d^0$ mesons with some contributions from B$_u$ and B$_s$ mesons. Different species of B mesons behave differently with respect to oscillations. Neutral B$_d^0$ and B$_s$ mesons do oscillate while charged B$_u$ mesons do not oscillate. In the following it was assumed that the oscillations of B$_s$ mesons have infinite frequency. Possible contributions from b-baryons to the sample were also neglected.

The purity of the tagging method was defined as $\eta = N_{correctly\ tagged\ events}/N_{total\ tagged\ events}$. It was assumed that the tagging purity is the same for all B mesons because the opposite-side tagging information has little correlation with the reconstructed B meson candidate.

For a given type of $B$-hadron (i.e. $d,\ u,\ s$), the distribution of the visible proper decay length $x$ is given by:

$$n_d^{non-osc}(x,K) = \frac{K}{c\tau_{B_d}} \exp(-\frac{Kx}{c\tau_{B_d}}) \cdot 0.5 \cdot (1 + (2\eta - 1)\cos(\Delta m \cdot Kx/c));$$

$$n_d^{osc}(x,K) = \frac{K}{c\tau_{B_d}} \exp(-\frac{Kx}{c\tau_{B_d}}) \cdot 0.5 \cdot (1 - (2\eta - 1)\cos(\Delta m \cdot Kx/c)); \quad (3)$$

$$n_u^{non-osc}(x,K) = \frac{K}{c\tau_{B_u}} \exp(-\frac{Kx}{c\tau_{B_u}}) \cdot \eta; \qquad n_u^{osc}(x,K) = \frac{K}{c\tau_{B_u}} \exp(-\frac{Kx}{c\tau_{B_u}}) \cdot (1-\eta); \quad (4)$$

$$n_s^{non-osc}(x,K) = n_s^{osc}(x,K) = \frac{K}{c\tau_{B_s}} \exp(-\frac{Kx}{c\tau_{B_s}}) \cdot 0.5, \quad (5)$$

where $K = P_T^{\mu \mathrm{D}^0}/P_T^B$ is a K-factor reflecting the difference between the observable and true momentum of the $B$-hadron and $\tau$ is the lifetime of $B$-hadrons taken from [2]. The $K$-factors were determined from the simulation using generator-level information for the computation of $p_T^B$ and $P_T^{\mu \mathrm{D}^0}$. The following decay channels of B mesons were considered: $B_d^0 \to \mu^+ \nu \mathrm{D}^{*-}$, $B_d^0 \to \mu^+ \nu \mathrm{D}^{**-} \to \mu^+ \nu \mathrm{D}^{*-} X$, $B^+ \to \mu^+ \nu \bar{\mathrm{D}}^{**0} \to \mu^+ \nu \mathrm{D}^{*-} X$ and $B_s^0 \to \mu^+ \nu \mathrm{D}^{*-} X$. Here and in the following the symbol "D$^{**}$" denotes both narrow and wide D$^{**}$ resonances, together with non-resonant D$\pi$ and D$^*\pi$ production. The slow pion from D$^{*-}$decay was not included in the $p_T(\mu \mathrm{D}^0)$ computation for the $K$-factors. The $K$-factors for all considered decays were combined into 3 groups: $B \to \mu^+ \nu \bar{\mathrm{D}}^* X$, $B \to \mu^+ \nu \bar{\mathrm{D}}^{**} X \to \mu^+ \nu \bar{\mathrm{D}}^* X$ and $B_s \to \mu^+ \nu \bar{\mathrm{D}}^* X$.

Transition to the measured VPDL, $x^M$ is achieved by integration over $K$-factors and resolution functions:

$$N_{(d,u,s),\ j}^{osc,\ non-osc}(x^M) = \int dx\ Res_j(x - x^M) \cdot Eff_j(x) \int dK\ D_j(K) \cdot \theta(x) \cdot n_{(d,u,s),\ j}^{osc,\ non-osc}(x,K). \quad (6)$$

Here $Res_j(x - x^M)$ is the detector resolution of the VPDL and $Eff_j(x)$ is the reconstruction efficiency for a given decay channel $j$ of this type of B meson. Both are determined from the simulation. The decay length resolution was parameterised by the sum of 3 Gaussians with the following parameters: widths 26, 56 and 141 microns; relative normalizations 0.423, 0.505 and 0.072 respectively. The step function $\theta(x)$ takes into account that only positive values of $x$ are possible ($x^M$ can have negative values due to resolution effects). The function $D_j(K)$ gives the normalized distribution of the $K$-factor in a given channel $j$.

The expected number of oscillated/non-oscillated events in the $i$-th bin of VPDL is equal to

$$N_i^{e,osc/non-osc} = \int_i dx^M \ (\sum_{f=u,d,s} \sum_j (Br_j \cdot N_{f,\ j}^{osc/non-osc}(x^M))) \quad (7)$$

Here the integration $\int_i dx^M$ is taken over a given interval $i$, the sum $\sum_j$ is taken over all decay channels $B \to \mu^+ \nu \mathrm{D}^{*-} X$ and $Br_j$ is the branching ratio of a given channel $j$.

The latest PDG values [2] were used for the $B$ decay branching fractions. Exploiting that semileptonic $B$ decays are saturated by decays to D, D$^*$ and D$^{**}$, and the isotopical invariance it was determined that the $B_d^0$ ( 85%) and $B^+$ ( 15%) decays give the main contributions into the sample. The $B_s$ contribution is small but it was taken into account and the corresponding uncertainty was studied (see Table II).

Finally, the expected value $A_i^e$ for interval $i$ of the measured VPDL is given by formula (2) with $N_i^{non-osc}$ and $N_i^{osc}$ substituted by $N_i^{e,non-osc}$ and $N_i^{e,osc}$.

The fit values of $\Delta m$ and $\eta$ were determined from the minimization of a $\chi^2(\Delta m,\eta)$ defined as:

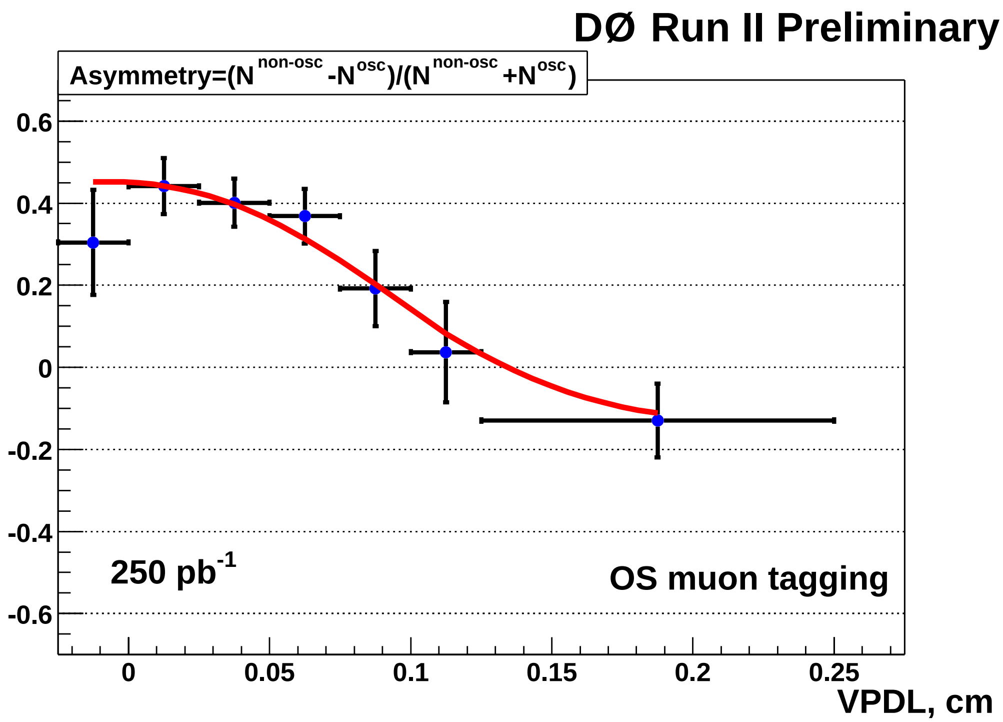


FIG. 3: The asymmetry in the D$^*$ sample as a function of the visible proper decay length in cm. The result of the minimization of (8) with $\Delta m = 0.506$ ps$^{-1}$ is the shown curve.

$$\chi^2(\Delta m, \eta) = \sum_i \frac{(A_i - A_i^e(\Delta m, \eta))^2}{\sigma^2(A_i)} \tag{8}$$

This results in:

$$\Delta m = 0.506 \pm 0.055 \text{ (stat) ps}^{-1} \qquad \eta = 73.0 \pm 2.1\% \tag{9}$$

The obtained values of $A_i^e$ in each bin are given in Table I. The value of $\chi^2/NDF$ in the minimum is 2.1/5. Fig.3 shows the asymmetry as function of VPDL together with the result of the fit.

## VII. SYSTEMATIC ERRORS

A summary of the systematic errors is given in Table II. It shows variations of $\Delta m$ and $\eta$ for each considered systematic effect.

The branching rates of B mesons used as input for minimization were varied by $1\sigma$.

The VPDL resolution, obtained from the simulation, was varied by a large factor, from 0.2 to 2, which significantly exceeds the estimated difference in resolution between data and simulation.

Variation of $K$-factors with $B$ momentum was neglected in this analysis. To check the impact of this assumption on the final result, their computation was repeated with a cut on $p_T(\mathrm{D}^0) > 5$ GeV/c, or by applying an additional cut at 4 GeV/c on $p_T$ of muon. The change of average value of $K$-factors did not exceed 2%, which was used as the estimate of the systematic uncertainty in their values.

The systematic error from incorrect modelling of the MC efficiency was estimated assuming all efficiencies equal to 100%.

The B meson lifetime was varied by one $\sigma$ to estimate the corresponding contribution to the systematic error.

Possible contributions with small lifetime can bias the oscillation wave at small values of VPDL. We checked how sensitive we are to these effects by dropping the first bin and redoing the minimization.

The procedure of determination of the number of $\mu^+ D^{*-}$ candidates in each VPDL bin gives the main contribution to the systematic error. To evaluate this contribution the numbers of $\mu^+ D^{*-}$ candidates were counted in the window

TABLE II: Systematic errors

| | variation | $\Delta m$ change | $\eta$ change |
|---|---|---|---|
| $Br(B_d^0 \to D^{*-}\mu^+\nu)$ | $5.53 \pm 0.023\%$ | 0.003 $\mathrm{ps}^{-1}$ | 0.0006 |
| $Br(B \to D^*\pi\mu\nu X)$ | $1.22 \pm 0.17\%$ | 0.009 $\mathrm{ps}^{-1}$ | 0.0002 |
| $Br(B_s \to D_s\mu^+\nu X)$ | $7.9 \pm 2.4\%$ | 0.001 $\mathrm{ps}^{-1}$ | 0.0040 |
| B lifetime | $502 \pm 5\mu$m | 0.004 $\mathrm{ps}^{-1}$ | 0.0020 |
| resolution function | $\times[0.2 \div 2]$ | 0.017 $\mathrm{ps}^{-1}$ | 0.0040 |
| alignment | $10\mu$m | 0.007 $\mathrm{ps}^{-1}$ | 0.0040 |
| k-factor | average value $\pm$ 2% | 0.009 $\mathrm{ps}^{-1}$ | 0.0004 |
| contributions with small lifetime | drop bin 1 in fit | 0.005 $\mathrm{ps}^{-1}$ | 0.0010 |
| MC efficiency | set to 100% | 0.014 $\mathrm{ps}^{-1}$ | 0.0030 |
| Fitting procedure | see text | 0.041 $\mathrm{ps}^{-1}$ | 0.0020 |
| Total systematic error | | 0.049 $\mathrm{ps}^{-1}$ | 0.0083 |

$0.141 < M(\bar{\mathrm{D}}^0\pi) - M(\bar{\mathrm{D}}^0) < 0.149$ GeV/c$^2$. The background was subtracted using the wrong sign distribution $\mu^+(K^+\pi^-)\pi^+$ with scale factor determined from the window $0.16 < M(\bar{\mathrm{D}}^0\pi) - M(\bar{\mathrm{D}}^0) < 0.18$ GeV/c$^2$.

## VIII. CONCLUSIONS

We reported a preliminary measurement of the $B_d^0$ meson oscillation frequency. The large semileptonic sample corresponding to approximately 250 pb$^{-1}$ of integrated luminosity, accumulated by DØ during period from April 2002 to January 2004, was analysed and more than 25000 ($\mu^+\mathrm{D}^{*-}X$) candidate events were selected for the analysis. Using these statistics, the $B_d^0$ meson oscillation frequency was measured to be equal to:

$$\Delta m = 0.506 \pm 0.055 \text{ (stat) } \pm 0.049 \text{ (syst) ps}^{-1} \tag{10}$$

This result is in agreement with the world average of $\Delta m = 0.502 \pm 0.007$ ps$^{-1}$.

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